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ATTN: Wen C. Masters, Program Manager
Code 311

SUBJECT: Annual Progress Report for ONR N00014-98-1-0165

Dear Dr. Masters:

In accordance with the requirements of the subject grant, please find enclosed an original and two (2) copies of the subject report.

If you have any technical questions, please call me at 310-206-2829. For any administrative questions, please call Mr. Olwin at 310-825-1664.

Sincerely yours,

James C. McWilliams

James C. McWilliams
Principal Investigator

Keith R. Olwin
Dept. Research Associate
and Executive Administrator

ATTACHMENTS

cc: Director, NRL
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14. ABSTRACT

The main subject of the contract is spontaneous emergence, dynamics, and properties of the coherent spatial patterns in oceanic flows. The oceanic regimes include penetrating convection with rotation, wind-driven circulation of the midlatitude ocean, thermohaline circulation, coastal currents near the U.S. West Coast, planetary boundary layers and surface gravity waves. Consideration is also given to interactions between the coherent patterns, material transport, and spontaneous low-frequency variability. Some of the results are used for developing improved computational algorithms and parameterizations for oceanic models.

15. SUBJECT TERMS

Coherent spatial patterns, material transport, oceanic flows

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Principal Investigator's Progress Report

COHERENT SPATIAL PATTERNS AND MATERIAL TRANSPORT IN OCEANIC FLOWS

ONR Contract Number ONR N00014-98-1-0165

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For the period 1 November 1998 to 31 October 1999

This contract is for theoretical and computational research on several canonical regimes of oceanic currents. Its organizing theme is the coherent spatial patterns which spontaneously emerge in the types of nonlinear fluid dynamics typical of these different regimes and which subsequently dominate both the flow evolution and the associated transport of material properties; a minor theme is developing improved computational algorithms and parameterizations for oceanic models. The progress report covers all relevant research by the Principal Investigator, which is broader than the particular activities paid for through this contract. Numerical references are to the appended Bibliography of active, relevant papers during the reporting period.

THEORY OF VORTICES, TURBULENCE, AND LAGRANGIAN DYNAMICS

Highlights in this subject category are (1) the interaction of plumes and balanced vortices during convection and (2) the limits and breakdown of the balanced manifold for rotating, stratified flows. In (1) several studies have been completed in a continuing collaboration with Dr. Sonya Legg (WHOI) on plume and mesoscale dynamics during oceanic deep convection: a statistical analysis of plume structure and dynamical balances (papers 5 and 8); an explanation of why temperature T and salinity S fluctuations are "spicy" (i.e., occur in linear combinations orthogonal to density fluctuations) due to passive advection of pre-existing mesoscale T and S gradients (paper 7); a demonstration of how convection increases the kinetic energy of mesoscale eddies, which in turn efficiently homogenizes T and S fields between but not within the eddies after the convection ceases (paper 9); and a demonstration of observational sampling biases due to trapping of constant-pressure floats in convergence zones (paper M5). In (2), Prof. Irad Yavneh (Technion) and I have identified a PDE regime boundary between "slow" balanced motions and faster inertia-gravity waves associated with a singularity of the nonlinear balance equations—which implies a change of type in more fundamental fluid equations—and at least sometimes with the onset of a "fast" instability (papers 11, 12, and M14). Associated Papers: 4,5,7,8,9,11,12,17,27,28,M3,M4,M5,M9,M14.

WIND-DRIVEN GYRES, ROSSBY WAVES, AND MESOSCALE EDDIES

Highlights in this subject category are (1) numerical solutions for idealized wind gyres at unprecedentedly high Reynolds number and (2) modeling material dispersion in wind gyres with stochastic differential equations. In (1) the statistical equilibrium circulation for steady wind forcing in a rectangular, mid-latitude domain shows two important changes in calculations at grid resolutions higher than are now feasible with oceanic general circulation models: the separation site and off-shore shape of the "gulf streams" show a topological bifurcation to a configuration of confluence of the boundary currents in the subtropical and subpolar gyres, and the mesoscale eddy field exhibits an outbreak of long-lived, isolated, small-scale coherent vortices (papers 23 and M11). In (2) we are developing a formalism for stochastically modeling particle motions in turbulent wind gyres as a generalized Markov process, taking into account horizontal inhomogeneity and anisotropy in the Lagrangian dispersion statistics (including both sub-diffusive and super-diffusive regimes) while satisfying nontrivial realizability constraints (papers M1-M2). Preliminary results indicate that this approach is quite accurate in characterizing the long-time material transports, including major barriers such as between the subtropical and subpolar gyres. Associated Papers: 1,2,23,25,26,M1,M2,M11,M13.

THERMOHALINE CIRCULATION

A new research direction is seeking a theoretical understanding of decadal- and basin-scale oscillations of the oceanic thermohaline circulation, which have been observed in many numerical calculations with oceanic general circulation models; this phenomenon is highly relevant for climate variability. The approach is to solve iteratively for the steady-state circulation in non-evolutionary equations and then solve for its unstable or least-stable eigenmodes for small-amplitude perturbations. This must be done for a 3D non-separable mean state, and thus linear algebra must be carried out with exceeding large matrices. The past year has been spent developing codes for these calculations, and we are now obtaining preliminary solutions. Associated Papers: 20,21,M8,M10.

COASTAL CURRENTS

Our primary effort here has been to develop a new model capable of realistic coastal simulations that we are applying both to the U.S. West Coast and more idealized problems. The new model has important algorithmic improvements in advection, topographic representation, time-stepping of stiff gravity waves, ecosystem and particulate dynamics, and open boundary conditions. The initial simulations have been for the mean seasonal cycle of the West Coast circulation at a sequence of grid-resolutions that extend to vigorous coastal eddy cycles involving topographically triggered "squirts and jets" in the cross-shore material transports. We are currently assessing this solution in comparison with CalCOFI surveys andwill be SST, SAR, color images, and altimetry. Future research will be to further develop the model by including embedded sub-domains for very fine resolution in particular locations. We also will develop idealized solutions for topography-jet-eddy interactions and material transport to investigate the influence of fine-scale boundary complexity. This research has had a long development and gestation period that is nearly over; one indication of its anticipated impact is the ORSMP/NOPP award for "Models of the Coastal Ocean off the West Coast of North America: A comparative study and synthesis of observations" (jointly with J. Allen (OSU) and T. Powell (UC Berkeley)). Associated Papers: 19,M6,M7,M12.

PLANETARY BOUNDARY LAYERS AND SURFACE GRAVITY WAVES

With Prof. Juan Restrepo (Arizona) I have developed a multi-scale perturbation theory of how weakly nonlinear surface gravity waves provide dynamical influences on the lower-frequency currents, largely through the action of the Lagrangian Stokes drift but also through altered surface boundary conditions (paper 16). This theory makes potentially significant predictions for near-surface Langmuir circulations, Ekman boundary-layer currents, near-surface material transport, and the interpretation of satellite radar altimetry measurements of sea level. In addition in a continuing collaboration with Dr. Peter Sullivan (NCAR), I am extending Large-Eddy Simulation (LES) models of atmospheric and oceanic boundary layers to include not only the wave-averaged dynamics above but other surface wave effects as well. The latter include "wave pumping", which excites wave-correlated motions that control the oceanic surface form stress and sustain mean vertical momentum and material fluxes near the surface, and "wave breaking", which injects small-scale kinetic energy and enhances the mixing efficiency in the upper ocean. Associated Papers: 13,16,18,24.

NUMERICAL METHODS AND PARAMETERIZATIONS FOR OCEAN MODELS

New algorithms and parameterizations developments are needed in our computational models for the above phenomena. Besides the development of the Regional Ocean Modeling System (which we are leading at UCLA; see above and paper M12), some other recent advances are a new quasi-monotone advection operator discretization (paper 22); a moving boundary for wave pumping in boundary-layer LES (paper 3); and a 3D anisotropic eddy viscosity parameterization which yields improved equatorial current in climate models (papers 6 and 10). Associated Papers: 3,6,10,14,15,22,24,M12.

PERSONNEL

The principal expenditures under this contract have been for parts the salary of Drs. Pavel Berloff (gyre dispersion) and Jeroen Molemaker (thermohaline oscillations). In the coming year, the salary support will be given to Berloff and Prof. Yavneh (Technion), who is spending a sabbatical year at UCLA.

August 1999

COHERENT SPATIAL PATTERNS AND MATERIAL TRANSPORT IN OCEANIC FLOWS

James C. McWilliams

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[M1] Berloff, P., and J.C. McWilliams: Stochastic modeling of inhomogeneous dispersion in oceanic wind gyres.

[M2] Bracco, A., P. Berloff, J.C. McWilliams, and A. Provenzale: A Lagrangian statistical analysis of oceanic wind gyres.

[M3] Graves, P., and J.C. McWilliams: An explanation of anti-cyclonic dominance of balanced vortices.

[M4] Huber, M., M. Ghil, and J.C. McWilliams, 1999: A Lagrangian investigation of large-scale atmospheric turbulence. *J. Atmos. Sci.*, to be submitted.

[M5] Legg, S., and J.C. McWilliams: Statistics of isobaric floats in a convecting eddy field.

[M6] Marchesiello, P., J.C. McWilliams, and A. Shchepetkin: The equilibrium circulation off the west coast of the United States.

[M7] Marchesiello, P., J.C. McWilliams, and A. Shchepetkin: Open boundary conditions for large-region coastal ocean models.

[M8] Molemaker, N., and J.C. McWilliams: Steady states and unstable modes of the 3D oceanic thermohaline circulation.

[M9] Morel, Y. and J.C. McWilliams: Effects of mixing on the stability of oceanic currents.

[M10] Saravanan, R., S.C. Doney, G. Danabasoglu, and J.C. McWilliams: Temperature-salinity correlations and spiciness dominance in oceanic decadal variability.

[M11] Siegel, A., J.B. Weiss, and J.C. McWilliams: Models of oceanic wind gyres at high Reynolds number.

[M12] Shchepetkin, Alexander, and J.C. McWilliams: The Regional Ocean Modelling System (ROMS): A split-explicit, free-surface, topography-following-coordinate ocean model.

[M13] Tailleux, R., and J.C. McWilliams: Vertical modal coupling of baroclinic Rossby waves in the ocean.

[M14] Yavneh, I., and J.C. McWilliams: Ageostrophic instabilities of co-rotating, stratified Taylor Couette flow: fuzziness and breakdown of the slow manifold.